All-optical switching and multistability in photonic structures with liquid crystal defects

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We demonstrate that one-dimensional photonic crystals with pure nematic liquid-crystal defects can operate as all-optical switching devices based on optical orientational nonlinearities of liquid crystals. We show that such a periodic structure is responsible for a modulated threshold of the optical Fréedericksz transition in the spectral domain, and this leads to all-optical switching and light-induced multistability. This effect has no quasi-statics electric field analogue, and it results from nonlinear coupling between light and a defect mode.

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The concept of photonic crystals [1] proposed two decades ago [2, 3] brought a new paradigm to achieve light propagation control in dielectric media. In such periodic photonic structures tuning may be achieved by using materials which are sensitive to external fields, including temperature, electric field, or light itself. In this context, nonlinear photonic crystals have retained much attention due to possible enhancement of nonlinear effects [4]. Among various nonlinear optical materials that can be implemented in actual photonic crystal devices, liquid crystals (LCs) have been recognized as an attractive alternative material [5] due to their unique sensitivity to external fields. Since then, many tunable photonic crystal devices based on LC tunability have been suggested and implemented either using complete or partial LC infiltration into the periodic dielectric structure. In the first case, the photonic bandgap is tuned due to refractive index changes of the global structure [6], while in the second case a LC-infiltrated layer or hole generates defect modes whose frequencies are controlled by local refractive index changes of LC [7]. The case of complete infiltration is the most studied one, and it was the first to be demonstrated; it concerns thermal [6] and electrical [8] tunability infiltrated one-, two- and three-dimensional photonic structures with LCs. There exist much less studies concerning *optical tuning*. One can mention the demonstration using photonic LC fibers [9, 10], one-dimensional [11] or planar [12, 13] photonic crystals using absorbing or dye-doped LCs. In these works the resonant interaction of light induces a change of the order parameter, phase transition or surface-mediated bulk realignment. However the non-resonant case, where well-known orientational optical nonlinearity of LC takes place [14], has only been explored recently in Ref. [15], where the optical Fréedericksz transition (OFT) was studied in a one-dimensional photonic crystal with a nematic liquid crystal (NLC) defect. It was shown that a NLC having a first-order OFT in the single slab case under linearly polarized excitation could be used as an optical switch and operate as an optical diode when the excitation wavelength matches a defect mode frequency. However, such first-order OFT materials are not common and the calculation was made with liquid crystal PAA [15], which has the nematic phase in the typical range of temperature $120-135°$C and thus prevents from applications in optical data processing.

In this Letter, we study the effects of the orientational optical nonlinearity of LCs in a one-dimensional periodic dielectric structure for a linearly polarized input beam. First, we demonstrate a nonlinear feedback due to coupling between light and a defect mode via orientational nonlinearities. This feedback could be *positive*, resulting in all-optical multistable switching, or *negative*, depend-

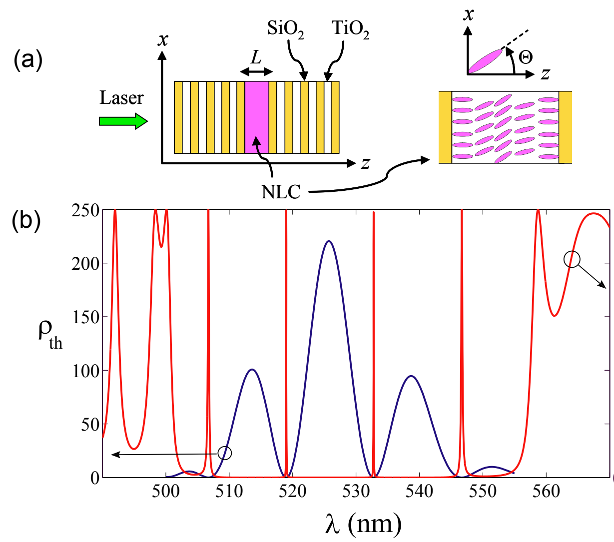

FIG. 1: (Color online) (a) Sketch of the multilayers periodic structure with an embedded NLC defect. (b) Transmission spectra of the unperturbed system (red) and normalized OFT threshold (blue).

ing on the wavelength detuning from a defect mode. Second, we demonstrate that this coupling leads to different types (first or second order) OFT in periodic structures for the same NLC material. While all-optical bistable switches based on photonic crystals are mainly restricted to inorganic devices [16], our results could be envisaged as a promising opportunity for LC infiltrated photonic crystals technology.

The structure studied in this Letter is made of ten bilayers of SiO_2 and TiO_2 on each side of a NLC layer having a homeotropic alignment (molecules are perpendicular to substrates), as shown in Fig. 1(a). The thicknesses of NLC, TiO_2 and SiO_2 layers are 5 μm, 134 nm and 143 nm respectively. The resulting structure has a bandgap centered around 530 nm that supports four defect modes, as shown in Fig. 1(b) where the transmission spectra of the unreoriented structure is presented. We choose the commercially available E7 liquid crystal which is nematic at room temperature and exhibits a second-order OFT for a single slab under linearly polarized excitation.

The optical properties of the proposed structure are considered to be within the plane wave approximation, so that the system depends only on coordinate z [Fig. 1(a)] and time t. The problem is conveniently solved by using the Berreman 4×4 matrix approach [17] where Maxwell's equations can be expressed as $\partial\mathbf{\Psi}/\partial z = ik_0\mathbf{D}\mathbf{\Psi}$, where $k_0 = 2\pi/\lambda$ is the wave vector in vacuum, $\mathbf{D}$ is the Berreman matrix that depends on dielectric permittivity tensor ϵ_{ij}, and $\mathbf{\Psi} = (E_x, H_y, E_y, -H_x)^T$ [17]. The E_z component of the light field is obtained from the constitutive equation $\partial_i\epsilon_{ij}E_j = 0$. The whole structure is divided into many layers with constant permittivity, which are described by constant matrices $\mathbf{D}_n$. While the thickness of the dielectric layers corresponds to thickness of actual materials, the liquid crystal layer is discretized into as many sublayers as necessary to ensure prescribed small variations from one sublayer to another. The resulting matrix thus writes $\mathbf{D} = \prod \mathbf{D}_n$. We obtain a light propagation problem for incident (i), transmitted (t) and reflected (r) amplitudes that writes $\mathbf{\Psi}^t = \mathbf{D}(\mathbf{\Psi}^i + \mathbf{\Psi}^r)$. Inside the NLC layer, the light field is coupled to the Euler-Lagrange equations that govern the dynamics of the director $\mathbf{n}(z,t)$ [i.e. unit vector associated with local averaged molecular orientation, see Fig. 1(a)] and account for dissipative, elastic, and electromagnetic contributions [14].

We further consider the propagation of light linearly polarized along x-axis and assume the director to be constrained in the (x,z) plane, which can be represented by the reorientation angle $\Theta(z,t)$ [Fig. 1(a)]. The problem is solved numerically via the modal expansion procedure detailed in Ref. [18] by searching the reorientation profile as $\Theta(z,t) = \sum_{n=1}^{N}\Theta_n(t)\sin(\pi z/L)$, where $N = 10$ is enough to ensure accurate results. We introduce the normalized intensity $\rho = |E_x^i|^2/I_{\rm lin}^0$, where $I_{\rm lin}^0$ is the OFT threshold for a single NLC slab and linearly polarized plane wave, and time $\tau = t/\tau_{\rm NLC}$, where $\tau_{\rm NLC}$ is the

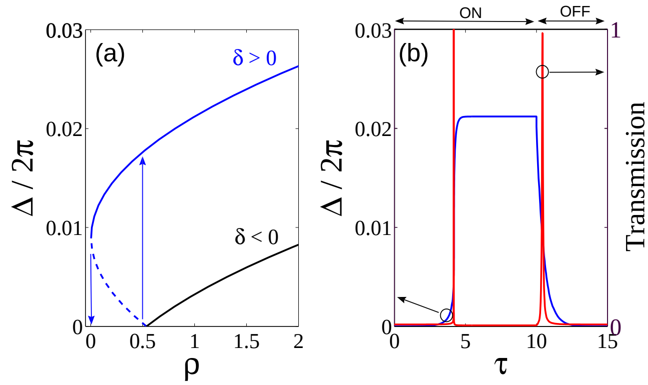

FIG. 2: (Color online) (a) Reorientation diagram near OFT for positive (blue) and negative (black) detuning $\delta = \pm 0.25$ nm around $\lambda_{\rm d} = 532.75$ nm. Solid (dashed) lines refers to stable (unstable) states. (b) Corresponding dynamics, for the $\delta > 0$, of phase delay Δ and pump light transmission for square-shaped temporal excitation with $\rho = 1$.

typical relaxation time [14]. Finally, we use

$$\Delta(\tau) = k_0 \int_0^L (n_e(z,\tau) - n_o)dz \ , \tag{1}$$

with $n_{o/e}$ being the ordinary and effective extraordinary refractive indexes, which is the total light-induced phase delay in the presence of reorientation. All NLC material parameters are those of Ref. [18], and the linear dispersion of refractive indices are all taken into account.

First, we calculate the OFT threshold $\rho_{\rm th}$ above which the NLC is reoriented for pump wavelength $\lambda_{\rm p}$ lying inside the bandgap [see Fig. 1(b)]. As was shown in Ref. [15], the reorientation threshold is drastically reduced at a defect wavelength with respect to the single NLC slab $\rho_{\rm th}(\lambda_{\rm d}) \ll 1$, caused by a very strong light confinement at the defect mode placed in a periodic structure. A reduction factor up to 10^3 is obtained for the present structure. In contrast, a significant increase of the threshold is observed when $\lambda_{\rm p}$ is strongly detuned from defect mode frequencies [Fig. 1(b)]. Indeed, the smaller the detuning parameter $\delta = \lambda_{\rm p} - \lambda_{\rm d}$ is, the better light confinement inside the defect NLC layer, which leads to the lower reorientation threshold.

Although the OFT threshold is independent of the sign of δ for $\lambda_{\rm p} \approx \lambda_{\rm d}$ (local parabolic approximation), the type of the light-induced reorientation strongly depends on it. This point is illustrated in Fig. 2(a) where the reorientation diagram Δ as a function of ρ calculated from (1) is shown for $\delta = \pm 0.25$ nm around $\lambda_{\rm d} = 532.75$ nm. A negative detuning leads to a second-order OFT, as it is the case for the NLC slab alone, whereas a positive detuning exhibits a first-order OFT with an relative hysteresis width of almost 100%. To understand this behavior we note that defect mode frequencies underwent a red-shift proportional to the increase of the averaged refractive index inside the NLC defect layer due to molecular reorientation. Consequently, recalling that the

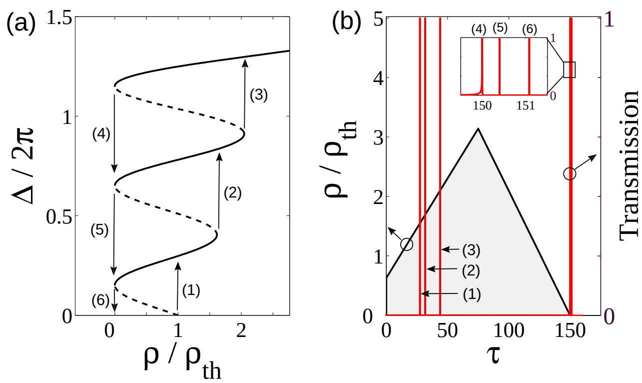

FIG. 3: (Color online) (a) Multistable reorientation diagram for positive detuning at $\lambda_\mathrm{p} = 537$ nm. Solid (dashed) lines refers to stable (unstable) states. (b) Corresponding dynamics of pump light transmission for triangle-shaped temporal excitation.

threshold intensity has a parabolic profile around defect modes $\rho_\mathrm{th}(\lambda_\mathrm{p}) - \rho_\mathrm{th}(\lambda_\mathrm{d}) \propto (\lambda_\mathrm{p} - \lambda_\mathrm{d})^2$, negative detuning $\delta < 0$ leads to a negative feedback and positive detuning $\delta > 0$ is accompanied by a positive feedback. All-optical bistable switching is thus achieved by properly chosen pumping wavelength $\lambda_\mathrm{p} > \lambda_\mathrm{d}$.

The dynamics of the all-optical switching process is illustrated in Fig. 2(b), where the unperturbed system is excited with $\delta > 0$ and $\rho > \rho_\mathrm{th}(\lambda_\mathrm{p})$ for $\tau < 10$ and $\rho = 0$ for $\tau > 10$. Two transmission peaks are observed, the first one at excitation stage and the second one during relaxation process. These peaks represent red-shift and blue-shift of the defect modes frequencies, respectively. Initial conditions at $\tau = 0$ are taken as $(\Theta_1 = 10^{-2}, \Theta_{2,\ldots,N} = 0)$, which mimics a thermal orientational fluctuation in the NLC slab. As a result, the smaller the detuning parameter is, the smaller intensity is the required to perform all-optical switching in periodic structures. A compromise has nevertheless to be found to preserve light-induced phase delay discontinuity since it vanishes for $\delta \to 0^+$.

Multistable all-optical switching can also be achieved in such a structure for larger intensities, caused by larger molecular reorientation resulting in larger changes of the refractive index. This leads to a possibility of many defect modes passing the pumping wavelength λ_p, and, consequently, to a series of reduction of the pumping intensity ρ giving reorientation boosts. An example is shown in Fig. 3(a) for $\lambda_\mathrm{p} = 537$ nm. The multistability is evidenced by several coexisting stable states in the reorientation diagram. The corresponding switching dynamics is shown in Fig. 3(b) when a linear ramp of excitation light intensity is used. Each of six peaks of the transmission dynamics is a reminiscent of a plateau in the reorientation diagram, as indicated by labels numbered (1-6).

In conclusions, we have predicted multistable all-optical switching resulting from an unique nonlinear coupling between light and defect modes in a periodic dielectric structure that contain a NLC defect layer. Moreover, depending on the pumping wavelength λ_p the same NLC material may demonstrate first- or second-order OFT in periodic structures. In contrast to other optically tunable photonic structures based on liquid crystals, the proposed system is based on orientational optical nonlinearity of liquid crystals. It is important to note that there is no quasi-statics electric field analog to the optical case studied here because the electro-optical tunability explored earlier [19] is not accompanied by a coupling between excitation field and defect modes. Additional functionalities are expected when non-planar molecular light-induced reordering takes place [18].

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[1] See, e.g., J.D. Joannopoulos, R.D. Meade, and J.N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, Princeton, NY, 1995), and references therein.

[2] E. Yablonovitch, "Inhibited spontaneous emission in solid-state physics and electronics," Phys. Rev. Lett. **58**, 2059 (1987).

[3] S. John, "Strong Localization of Photons in Certain Disordered Dielectric Superlattices," Phys. Rev. Lett. **58**, 2486 (1987).

[4] M. Soljačić and J.D. Joannopoulos, "Enhancement of nonlinear effects using photonic crystals," Nature Mater. **3**, 211 (2004).

[5] K. Busch and S. John, "Liquid-crystal photonic-band-gap materials: The tunable electromagnetic vacuum," Phys. Rev. Lett. **83**, 967 (1999).

[6] K. Yoshino, Y. Shimoda, Y. Kawagishi, K. Nakayama, and M. Ozaki, "Temperature tuning of the stop band in transmission spectra of liquid-crystal infiltrated synthetic opal as tunable photonic crystal," Appl. Phys. Lett. **75**, 932 (1999).

[7] Y.-K. Ha, Y.-C. Yang, J.-E. Kim, H. Y. Parka, C.-S. Kee, H. Lim, and J.-C. Lee, "Tunable omnidirectional reflection bands and defect modes of a one-dimensional photonic band gap structure with liquid crystals," Appl. Phys. Lett. **79**, 15 (2001).

[8] D. Kang, J. E. Maclennan, N. A. Clark, A. A. Zakhidov, and R. H. Baughman, "Electro-optic Behavior of Liquid-Crystal-Filled Silica Opal Photonic Crystals: Effect of Liquid-Crystal Alignment," Phys. Rev. Lett. **86**, 4052 (2001).

[9] T.T. Alkeskojld, L.A. Bjarklev, D.S. Hermann, Anawati, J. Broeng, J. Li, and S.T. Wu, "All-optical modulation in dye-doped nematic liquid crystal photonic bandgap fibers," Opt. Express **12**, 5857 (2004).

[10] J. Tuominen, H.J. Hoffrén, and H. Ludvigsen, "All-optical switch based on liquid-crystal infiltrated photonic bandgap fiber in transverse configuration," J. Eu-

rop. Opt. Soc. Rap. Public. **2**, 07016 (2007).
[11] H. Yoshida, C. H. Lee, Y. Miura, A. Fujii, and M. Ozaki, "Optical tuning and switching of photonic defect modes in cholesteric liquid crystals," Appl. Phys. Lett. **90**, 071107 (2007).
[12] B. Maune, J. Witzens, T. Baehr-Jones, M. Kolodrubetz, H. Atwater, A. Scherer, R. Hagen, and Y. Qiu, "Optically triggered Q-switched photonic crystal laser," Opt. Express **13**, 4699 (2005).
[13] P. El-Kallassi, R. Ferrini, L. Zuppiroli, N. Le Thomas, R. Houdré, A. Berrier, S. Anand, and A. Talneau, "Optical tuning of planar photonic crystals infiltrated with organic molecules," J. Opt. Soc. Am. B **24**, 2165 (2007).
[14] N.V. Tabiryan, A.V. Sukhov, and B.Ya. Zel'dovich, "The orientational optical nonlinearity of liquid crystals," Mol. Cryst. Liq. Cryst. **136**, 1 (1986).
[15] A. E. Miroshnichenko, I. Pinkevych, and Y. S. Kivshar, "Tunable all-optical switching in periodic structures with liquid-crystal defects," Opt. Express **14**, 2839 (2006).
[16] M. Notomi, A. Shinya, S. Mitsugi, G. Kira, E. Kuramochi, and T. Tanabe, "Optical bistable switching action of Si high-Q photonic-crystal nanocavities," Opt. Express **13**, 2678 (2005).
[17] D. W. Berreman, "Optics in stratified and anisotropic media : 4×4-matrix formulation," J. Opt. Soc. Am. **62**, 502-510 (1972).
[18] E. Brasselet, T. V. Galstian, L. J. Dubé, D. O. Krimer, and L. Kramer, "Bifurcation analysis of optically induced dynamics in nematic liquid crystals: circular polarization at normal incidence," J. Opt. Soc. Am. B **22**, 1671 (2005).
[19] R. Ozaki, H. Moritake, K. Yoshino, and M. Ozaki, "Analysis of defect mode switching response in one-dimensional photonic crystal with a nematic liquid crystal defect layer," J. Appl. Phys. **101**, 033503 (2007).